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RESEARCH MEMORANDUM

EFFECT OF MAGNITUDE OF VIBRATORY LOAD SUPERIMPOSED ON MEAN TENSILE LOAD ON MECHANISM OF AND TIME TO FRACTURE OF SPECIMENS AND CORRELATION TO ENGINE BLADE

By Robert R. Ferguson

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
November 13, 1952

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RESEARCH MEMORANDUM

EFFECT OF MAGNITUDE OF VIBRATORY LOAD SUPERIMPOSED ON MEAN TENSILE LOAD ON MECHANISM OF AND TIME TO FRACTURE OF SPECIMENS AND CORRELATION TO ENGINE BLADE

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SUMMARY

Tensile fatigue tests were run on seven turbine-blade alloys at a temperature of 1500° F and a mean stress of 22,000 pounds per square inch with superimposed alternating stresses of 0, ±5000, ±10,000, and ±15,000 pounds per square inch. These conditions were selected so that the results could be compared with the performance of the seven alloys as turbine blades tested in a J33-9 turbojet engine.

The same three types of fracture occurring in turbine blades - stress-rupture, stress-rupture followed by fatigue, and fatigue - were obtained in the specimens. The type of fracture obtained was found to be a function of the material and the magnitude of the alternating stress. With increasing alternating stress, the mechanism of failure changed from stress rupture to stress rupture followed by fatigue and then to fatigue.

INTRODUCTION

The approximate stress state at the failure section of a turbine blade may be considered as composed of a combination of a centrifugal stress due to the rotation of the blade and a flexual stress due to the vibration of the blade. The centrifugal stress can be easily calculated (reference 1). The range of vibratory stress on the surface of a blade near the base of the airfoil in a J33-9 turbojet engine under service conditions has been measured by high-temperature resistance-wire strain gages and found to be in the range from 4000 to 8000 pounds per square inch (reference 2). This measurement, however, gives no indication of the magnitude of the vibratory stress at the failure zone of the blade.

From the examination of fractures of turbine blades tested to failure in turbojet engines at the NACA Lewis laboratory, three types of mechanism of fracture have been noted (reference 3). The fractured surface on some

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of the blades resembled the texture of the fracture of specimens tested in stress rupture in that the fracture was rough, jagged, and intercrystalline (fig. 1(a)). The airfoil surface adjacent to the fracture also showed intercrystalline cracking. The blade fractures of this type were referred to as "stress-rupture" fractures. The fractured surface on other blades resembled the fractures characteristic of fatigue in that the 2534 fracture had an area that was smooth and transcrystalline (fig. 1(b)), with the airfoil surface adjacent to the fracture not showing any additional cracking. These fractures were referred to as "fatigue" fractures. On other blades the fractures appeared to be a combination of the previous two in that the fracture surface comprised a small area that was rough and intercrystalline followed by a smooth transcrystalline area (fig. 1(c)). The airfoil surface adjacent to the fracture again showed some intercrystalline cracking. In this case, fracture was believed to start first as a stress-rupture crack that acted as a stress raiser causing the mechanism of the crack propagation to change from stress rupture to fatigue. These fractures were referred to as "stress rupture followed by fatigue". (In all cases the blade failed finally in tension because the load-carrying area had become too small. Thus all blades will show a large area of rough fracture surface.)

In an investigation at the Lewis laboratory, the times to failure of turbine blades of nine alloys tested in a J33-9 turbojet engine were compared with the times to failure of specimens of the alloys tested in stress rupture at a stress and temperature equal to the blade centrifugal stress and temperature (reference 3). Except for one alloy, all alloys that showed fractures of the stress-rupture or stress rupture followed by fatigue types in the engine had approximately the same engine life as the specimens of the alloys tested in stress rupture in the laboratory. The blades of the alloys that showed fatigue fractures had a shorter life than the specimens of these alloys tested in stress rupture.

The fact that the different alloys showed different mechanisms of failure as turbine blades and that the alloys that failed in fatigue in the engine had short blade lives as compared with their stress-rupture life raises several questions. Do vibratory stresses have the same effect on life and apparent mechanism of failure of the different turbine blade alloys? Does a blade fatigue failure definitely mean that the life of the blade has been appreciably reduced by the vibratory stress?

The turbine-blade-alloy investigation reported herein was undertaken to obtain more information about the combined effects of centrifugal and vibratory stresses on time to failure as compared with the effect of the centrifugal stress, alone.

Tensile fatigue tests were run at 1500° F on specimens of seven turbine blade alloys at a mean stress of 22,000 pounds per square inch with superimposed alternating tensile stresses of 0, ±5000, ±10,000, and

±15,000 pounds per square inch. One specimen was tested at each alternating stress for each alloy. A more direct comparison of turbine blades would be the measurement of the effect of superimposed bending stress upon a mean tensile stress but equipment for imposing the necessary loading was not available at this laboratory. A test temperature of 1500° F and a mean stress of 22,000 pounds per square inch were chosen to correspond to the temperature and average centrifugal stress at the failure section of the blades tested and reported in reference 3. Tests were run at an alternating stress of zero so that the effect of the centrifugal stress alone could be determined and compared with the combined effect of the vibratory and centrifugal stresses. In order to determine whether or not the results obtained from the round cross-sectional specimens were applicable to shapes with thin edges such as turbine blades, the alloys S-816 and N-155 were tested in the form of both diamond and round cross sections.

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MATERIALS

The alloys investigated and their compositions are listed in table I. The heat treatments given the alloys, the grain size and the hardness after heat treatment, and the type of specimen tested for each alloy are given in table II. Specimens of Stellite 21, X-40, and S-816 with diamond cross sections were cast at a pouring temperature of 2700° to 2750° F and a mold preheat temperature of 1500° F by centrifugal casting. The specimens of each material tested were from the same mold. These cast specimens had the dimensions shown in figure 2(a) except that the sharp edge on the diamond was from 0.005 to 0.010 inch in width. The cast specimens were vapor blasted with number 80 grit quartz at an air pressure of 120 pounds per square inch. Round cross-sectional specimens (fig. 2(b)) of S-816, N-155, Refractalloy 26, and Inconel X were machined from heat-treated bar stock. A few diamond cross-sectional specimens of S-816 and N-155 of the shape shown in figure 2(b) except for a 3/8-inch length of uniform cross section at the center were also machined from bar stock. The test section of the machined specimens were polished with successively finer grades of emery paper and finished with grade 2/0 in the axial direction.

EQUIPMENT AND PROCEDURE

Fatigue testing equipment. - The fatigue tests were conducted on direct repeated-stress testing machines which imposed an axial load (5000 lb max.) at the rate of 2000 cycles per minute. Figure 3 is a photograph of one of the machines that has been modified for testing at elevated temperatures. This machine is so designed that two specimens can be tested independently at the same time and is equipped with a load maintainer that sustains the same specimen load during a test by compensating for the creep of the specimen.

A loading lever E, actuated by the connecting rod C, the adjustable cam B, and the drive pulley A, applies the variable load (fig. 3). The force is transmitted by a parallelogram system of four steel-plate fulcrums H, designed to produce straight-line motion and axial loading of the specimen. The upper end of the specimen assembly is connected to a hydraulic operated piston O.

The ends of the specimen are threaded into specimen adapters J and L. The specimen adapter assembly is then placed inside the furnace J and the threaded ends of the specimen adapters screwed into the universal joints I and M. The upper end of the specimen assembly is fastened to the piston O by nuts N and P.

The mean tensile load is applied with the cam throw at zero to the specimen by upward operation of piston O, and is measured by means of the calibrated dial bar F in terms of the bending induced in the loading lever. The cam throw is then adjusted so that as the cam is slowly rotated by hand, the desired maximum and minimum loads - measured by the dial bar - are applied. Contact D is then positioned above the loading lever to just clear the top of the loading lever at its most upward position and contact G is positioned below the loading lever to just clear the bottom of loading lever at its most downward position. During operation at temperature, the elongation of the specimen reduces the deflection at the middle of the load lever resulting in the lever striking contact G. An electric charge is dissipated through the contact which causes piston O to move in upward direction until the loading lever clears the bottom contact on its downward stroke. Contact D operates piston O in the downward direction if the loading stresses become too high.

The furnace K which is used to maintain the specimen at temperature is of the shunt-wound type to permit the control of the heat distribution.

Stress control. - The maximum and minimum of the stress cycle were maintained within ±700 pounds per square inch of the nominal maximum and minimum stress. During a test, when the maximum and minimum loads were applied to the specimen, another stress cycle existed which consisted of a slow decrease of approximately 500 pounds per square inch due to the creep of the specimen and a quick reapplication of this load by the load maintainer. The loads measured and recorded were the maximum and minimum loads applied to the specimen by slow manual rotation of the drive pulley. During operation at operating frequency, the minimum load is slightly decreased and the maximum load slightly increased because of inertia loading of the load lever increasing the range of the alternating load from 3 to 7 percent in both directions from the mean load. The mean load is not affected by the inertia loading of the load lever. Accordingly, the range of the alternating loads recorded are 3 to 7 percent less than the actual alternating load applied to the specimen.

<u>Temperature control</u>. - The specimens were heated to 1500° F in approximately 1 hour and held at this temperature from 2 to 4 hours prior to the start of the test. During the test, the temperature was maintained at 1500° ±5° F.

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RESULTS AND DISCUSSION

<u>Types of specimen fracture</u>. - The specimen life and type of specimen fracture at each alternating stress for the seven alloys is tabulated in table III. Specimen fractures of all three types occurring in turbine blades were obtained in the fatigue machine. Figure 4 is a photograph of the fractured surfaces of tested specimens fabricated of the alloy Stellite 21 illustrating the three types of specimen fracture obtained: stress rupture, fatigue, and stress rupture followed by fatigue. The specimen that showed a stress-rupture-followed-by-fatigue type fracture (fig. 4(b)) appeared to start as a stress-rupture crack which acted as a stress raiser causing the mechanism to change from stress rupture to fatigue. The resemblance between the three types of specimen fracture and the three types of blade fracture can be noted by comparing these fractures with the blade fractures shown in figure 1.

Photographs showing the appearance of typical fractures for some of the other alloys tested at different alternating stresses are shown in figure 5. The stress-rupture area in the S-816 specimen which failed by stress rupture followed by fatigue was so small that examination of the fracture at a magnification was necessary to detect the stress-rupture zone that initiated the fatigue zone (figs. 5(a) and 5(b)). The fractures of the specimens of Inconel X and Refractalloy 26 had a coarse granular appearance (figs. 5(c) and 5(d)). The areas in the specimens of Refractalloy 26 that failed by fatigue still had this granular appearance except that many of the areas had large flat facets approximately normal to the direction of loading (fig. 5(d)). All specimens of Inconel X failed by stress rupture; however, the roughness of the surface of the fractures decreased with increasing alternating stress (fig. 5(c)).

<u>Effect of alternating stress on mechanism of failure</u>. - The type of specimen fracture obtained was a function of the alloy and the magnitude of the alternating stress. With increasing alternating stress, the failure mechanisms of the alloys changed from stress rupture to stress rupture followed by fatigue and then to fatigue.

The alloy that had a fatigue failure at the lowest alternating stress was cast S-816 which failed by fatigue at ±5000 pounds per square inch, the lowest alternating stress at which the specimens were tested. The alloys that developed their first fatigue failures at the next largest alternating stress at which the specimens were tested (±10,000 psi) were cast Stellite 21 and wrought S-816. The alloys N-155, X-40, and

Refractalloy 26 developed their first fatigue failures at an alternating stress of ±15,000 pounds per square inch. Inconel X did not show a fatigue fracture.

The best agreement between the mechanism of failure of the materials as turbine blades in a jet engine and as specimens tested at different alternating stress levels is obtained at the alternating stress level of ±5000 pounds per square inch. The types of failure obtained for the alloys as specimens tested at an alternating stress of ±5000 pounds per square inch and as blades are tabulated in table IV. Six of the seven alloys tested had the same type of failure for specimens tested at an alternating stress of ±5000 pounds per square inch and for blades. Provided that the greater frequency of stress cycling in the turbine does not shift the relation between the magnitude of the alternating stress and the failure mechanism of the alloys, this would indicate that the alternating stress at the failure zone in these blade tests was probably near the range of ±5000 pounds per square inch.

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Effect of alternating stress on specimen life. - The variation of specimen life with the alternating stress at which the specimen was tested is shown in figure 6.

Six of the seven alloys investigated appear to show a general trend toward decrease in life with increasing alternating loads as would be expected. The only exception is X-40. In the case of this alloy it seems likely that the scatter of data is very large as it is not expected that the life will be increased by 50 percent with an alternating stress of 10,000 pounds per square inch over that of an alternating stress of zero. If this scatter is indicative, considerably more tests would be required to establish the shape of this curve clearly.

When the remaining six alloys are considered at an alternating stress of ±5000 pounds per square inch, the change in life varies from a 22-percent increase for N-155 to a 37-percent decrease for cast S-816. Only N-155 showed an increase in life. A similar increase in life for N-155 was found in other fatigue tests reported in reference 4. From these data it might be expected that superimposing a vibratory stress of ±5000 pounds per square inch on a blade would result in a decrease in life of generally less than 37 percent. This value appears large until it is noted that, based on reported rupture data for these alloys, a 1000-pound-per-square-inch increase in the centrifugal stress alone would decrease the life about 30 percent on an average.

If the life of the alloy is not influenced by frequency of stress cycling, the low vibratory stress indicated by this investigation would have little effect on the life of the blades as compared with the effect of centrifugal stress. This was found to be the case for alloys N-155, S-816, Stellite 21, Nimonic 80, and Hastelloy B as the average life of these alloys used as turbine blades was within 19 percent of the life of specimens removed from untested blades and tested for stress rupture at a stress equal to the centrifugal stress calculated to exist in the blade (reference 3). The average life of blades of cast S-816 and Refractalloy 26 had appreciably shorter life in the J33-9 turbojet engine than specimens removed from untested blades and tested for stress rupture. The specimen of cast S-816 tested at an alternating stress of ±5000 pounds per square inch did show approximately the same percentage reduction in life as the cast S-816 blades (40 percent). The specimen of Refractalloy 26 tested at an alternating stress of ±5000 pounds per square inch shows a reduction in life of 13 percent as compared with a reduction of 53 percent for the blades fabricated of Refractalloy 26. For this reason, the shorter life of Refractalloy 26 in the turbine as compared with its stress-rupture life is probably not due to the effect of the alternating stress in the turbine blade.

Superimposing an alternating stress of ±5000 pounds per square inch on a preload, however, may cause a greater reduction in life on specimens which have stress raisers in the surface, either in the form of scratches or nonhomogeneities in the alloy.

Effect of alternating stress on reductions of area of fractured specimens. - A plot of the reduction of area of the fractured specimens against the alternating stress at which the specimens of wrought alloy was tested is shown in figure 7. Superimposing an alternating stress on a mean tensile stress resulted in less reduction of area at fracture. The wrought alloys S-816, Inconel X, and Refractalloy 26 had 50 percent less reduction of area at an alternating stress of ±15,000 pounds per square inch than at an alternating stress of zero.

Effect of specimen shape on life. - The test results obtained on the specimen of N-155 and S-816 with diamond and round cross sections are tabulated in table III and plotted in figure 8.

The sharp edges on the wrought S-816 diamond-shaped specimen at an alternating stress of zero were more susceptible to the development of cracks than the flat surfaces on this specimen or the rounded surfaces on the S-816 round-shaped specimen at an alternating stress of zero (fig. 9). The round specimen contains no surface cracks aside from those next to the fracture; the diamond specimen contains many cracks along the sharp edges. The same phenomenon was observed on cast diamond and round Stellite 21 specimens in stress-rupture test at 1500° F for effect of specimen shape on stress-rupture life (reference 5). No effect of shape on stress-rupture life was found and it was concluded that the cracks that developed on the sharp edges of the diamond specimens did not reduce the life because of the static loading. However, it was suggested that in the case of an alternating load the cracks on the sharp edges of the diamond specimen may act as stress raisers and result in a reduction of life.

The diamond-shaped specimens of S-816 tested at ±5000 pounds per square inch and ±10,000 pounds per square inch still had approximately the same life as the round specimens tested at these alternating stresses. No edge cracks were visible on these specimens along the edge at which failure started (fig. 9). Edge cracks were visible on the diamond-shaped specimens on the opposite edge from which failure started. These cracks probably developed after failure started and were caused by the higher stresses due to the reduced cross-sectional area supporting the applied loads. 2534

Failure started at the sharp edge of only the diamond-shaped specimen of N-155 tested at an alternating stress of ±15,000 pounds per square inch. This diamond-shaped specimen had approximately the same life as the round specimen tested at this alternating stress. Failure on the other N-155 diamond-shaped specimens, all of which failed by stress rupture, started near the center between the two sharp edges, thus suggesting that the sharp edges were not of prime importance in initiating failure. Failure started in the interior of the round-shaped N-155 specimens that failed by stress rupture. The round and diamond specimens of N-155 that failed by stress rupture showed necking which resulted in failure starting in the interior of the cross section for the round specimens and at the center for the diamond specimens because of the biaxial stress state created at the center of the specimens by the necking process (reference 6).

No significant difference was found between the strengths of the round and diamond cross-sectional specimens for the alloys N-155 and S-816.

The amount of surface cracking adjacent to the fracture decreased with increasing alternating load on the specimens of S-816. The many edge cracks common on the sharp edges of specimens tested in stress rupture did not develop along the sharp edges at which failure started on the S-816 specimens tested under an alternating load.

CONCLUDING REMARKS

It was found that the three types of fracture occurring in turbine blades could be produced in specimens of an alloy tested in tensile fatigue. The type of fracture obtained at a constant mean stress was determined to be a function of the alloy and the magnitude of the alternating load. The failure mechanism of the specimens tested changed from stress rupture to stress rupture followed by fatigue and then to fatigue with increasing alternating stress.

Of the alloys investigated, cast S-816 was the most sensitive to the effect of alternating stress on failure mechanism. It exhibited a fatigue failure at an alternating stress of ±5000 pounds per square inch. Inconel X was the most insensitive and did not show a fatigue failure at an alternating stress of ±15,000 pounds per square inch.

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If in a particular turbojet engine, blades of some alloys failed by what appears to be fatigue, whereas blades of other alloys failed by stress rupture, the vibratory stress is not necessarily greater in the blades of some alloys than in others. The results indicate that different failure mechanisms of blades of different alloys could be due to differences in sensitivity of the alloys to the vibratory stress and not due to differences in magnitude of vibratory stress. (The fact that the observed failure mechanisms of six of the seven alloys tested were the same in the turbine as at on alternating stress of ±5000 psi in the testing machine indicates that even though the observed failure mechanisms differed for the various alloys the actual vibratory stress in the blades of the different alloys in a jet engine may still be the same.)

Turbine-blade failures due to fatigue indicate that the life of the blades probably has been reduced by vibratory stress. For the specimen that failed by a fatigue mechanism at the smallest alternating stress, the average reduction in life for the alloys tested is 45 percent.

Superimposing an axial alternating stress of the relatively low magnitude indicated by the mechanism of failure of the alloys in turbine blades of a turbojet engine on a mean tensile load did not appreciably reduce specimen life (maximum reduction measured, 37 percent; average reduction, 10 percent). Therefore, the fatigue failure of the blades having an abnormally short life (reduction of life greater than 40 percent) is probably due to a possible greater sensitivity of certain alloys to the high-frequency blade vibration found in operating turbines, flaws in the material that act as stress raisers, unusual amplitudes and modes of vibration, or due to the possible greater effect on certain alloys of superimposed alternating bending loads than alternating tensile loads.

The fact that alloys react differently to superimposed alternating loads indicates that a better criterion than stress-rupture testing for evaluating the relative performance of alloys as turbine blades may be noting the effect of superimposed alternating stresses on the life of the alloys.

For the alloys at one mean stress and at one temperature, the superimposed alternating stress against specimen life curves were obtained and the magnitude of the alternating stress at which the failure mechanism changes were determined. The shape of these curves and the alternating stress at which the failure mechanism changes probably varies with the mean stress and test temperature.

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TABLE I - CHEMICAL COMPOSITION OF ALLOYS INVESTIGATED

Alloy	Chemical Composition (percent by weight)													
	C	Mn	Si	P	S	Cr	Ni	Co	Mo	S	Cb	Ti	Al	Fe	Others
Stellite 21[a]	0.27	1.00 max	1.00 max	--	--	27.00	2.75	bal.	5.[illegible]0	--	--	--	--	2.00 max	B, 0.007 max
Cast S-816[a]	.37	1.50	1.00 max	0.040 max	0.030 max	20.00	20.00	40.00 min	4.00	4.00	4.00	--	--	5.00 max	---
X-40[a]	.50	1.00 max	1.00 max	.040 max	.04 max	25.50	10.50	bal.	--	7.50	--	--	--	2.00 max	---
Inconel X[a]	.08 max	.65	.50 max	--	.01 max	15.00	73.00	1.00 max	--	--	1.00	2.50	0.70	7.00	Cu, .20 max
Refractalloy 26[a]	.08 max	.70	1.00	.040 max	.030 max	18.00	37.00	20.00	3.00	--	--	2.90	0.50 max	bal.	---
N-155[b]	.13	1.88	.57	.022	.023	21.25	19.57	19.08	3.68	2.35	1.11	--	--	--	N_2, .10
Wrought S-816[b]	.40	1.45	.63	.005	.008	19.93	19.80	42.02	3.90	3.81	4.07	--	--	3.35	Ta, .27 Cu, .09

[a]Nominal composition.
[b]Actual composition.

TABLE II - HEAT TREATMENT, HARDNESS, GRAIN SIZE, AND TYPE OF SPECIMEN FOR EACH ALLOY

Alloys	Heat Treatment	Rockwell Hardness	Grain Size			Type of Specimen
			Predominant A.S.T.M. grain size	Average number of grains in diamond cross-section	Average number of grains per cross-sectional square in.	
Cast Stellite 21	None	C-24 to C-27	---	35	875	Diamond cross section
Cast S-816	None	B-97	---	15	375	Diamond cross section
Cast X-40	None	----	---	60	1500	Diamond cross section
Wrought N-155	1 hr at 2200° F; water quenched; 16 hr at 1400° F; air cooled	B-98	4-5	--	--	Round and diamond cross section
Wrought S-816	1 hr at 2150° F; water quenched; 16 hr at 1400° F; air cooled	C-26	6-8	--	--	Round and diamond cross section
Wrought Refractalloy 26	1 hr at 2100° F; air cooled; 20 hr at 1500° F; air cooled; 20 hr at 1350° F; air cooled	----	3	--	--	Round cross section
Wrought Inconel X	2 hr at 2100° F; air cooled; 24 hr at 1550° F; air cooled; 20 hr at 1300° F; air cooled	----	3	--	--	Round cross section

TABLE III - EFFECT OF ALTERNATING STRESS ON TYPE OF FRACTURE AND

TIME TO FAILURE

Material	Alternating stress, psi							
	±0		±5000		±10,000		±15,000	
	Specimen life (hr)	Type of fracture (a)	Specimen life (hr)	Type of fracture (a)	Specimen life (hr)	Type of fracture (a)	Specimen life (hr)	Type of fracture (a)
N-155								
Round specimen	17.8	SR	21.8	SR	15.9	SR	7.5	F
Diamond specimen	21.5	SR	17.0	SR	18.3	SR	4.9	F
Stellite 21	44.8	SR	39.0	SR-F	10.5	F	5.5	F
X-40	200.0	SR	240.0	SR	305.5	SR	153.8	F
Refractalloy 26	213.7	SR	185.5	SR-F	167.9	SR-F	131.7	F
Cast S-816	220.4	SR	139.8	F	146.7	F	94.2	F
Wrought S-816								
Round specimen	252.0	SR	184.7	SR-F	204.5	F	113.7	F
Diamond specimen	193.5	SR	228.8	SR-F	156.5	F		
Inconel X	403.0	SR	310.8	SR	305.2	SR	235.7	SR

[a]SR stress-rupture fracture; SR-F stress-rupture-followed-by-fatigue fracture; F fatigue fracture.

TABLE IV - COMPARISON OF TYPES OF BLADE FAILURE WITH TYPE OF

SPECIMEN FAILURE AT ALTERNATING STRESS OF

±5000 POUNDS PER SQUARE INCH

Materials	Type of blade failure	Type of specimen failure at alternating stress of ±5000 psi (a)
N-155	5 blades by SR; 1 blade by SR-F	SR
Inconel X	3 blades by SR	SR
Wrought S-816	5 blades by SR-F	SR-F
Stellite 21	2 blades by SR-F; 1 blade by SR	SR-F
Cast S-816	4 blades by F	F
Refractalloy 26	3 blades by SR; 1 blade by SR-F	SR-F
X-40	1 blade by F	SR

[a]SR stress rupture; SR-F stress rupture followed by fatigue; F fatigue.

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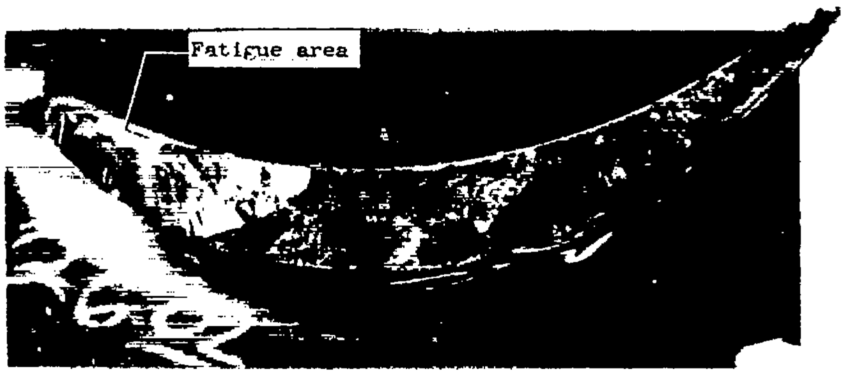
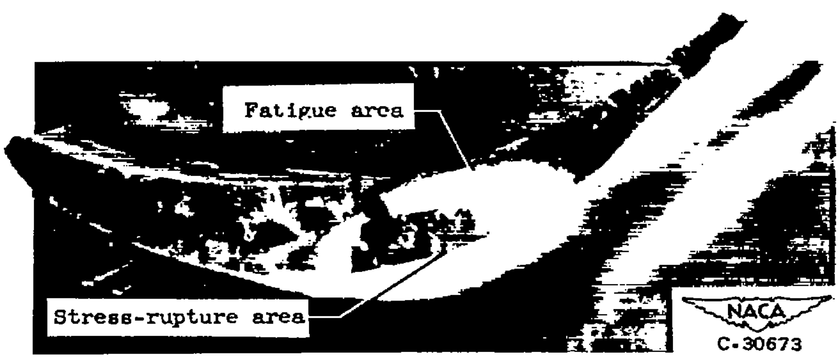
(a) Stress-rupture fracture.



(b) Fatigue fracture.



(c) Stress rupture followed by fatigue fracture.

Figure 1. - Types of turbine-blade fracture observed in engine tests (reference 3).

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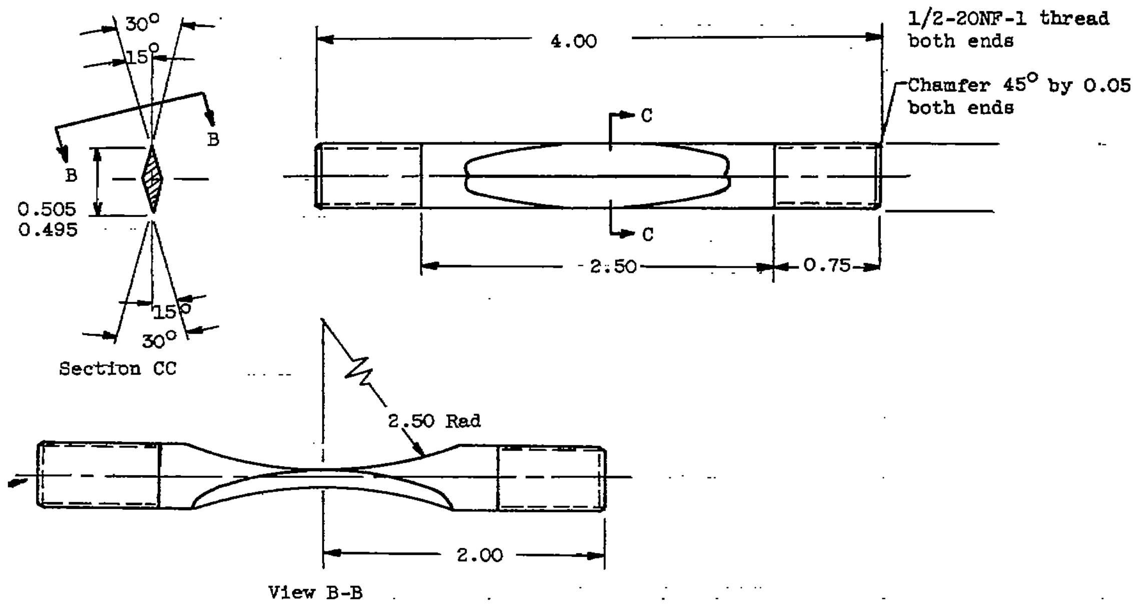
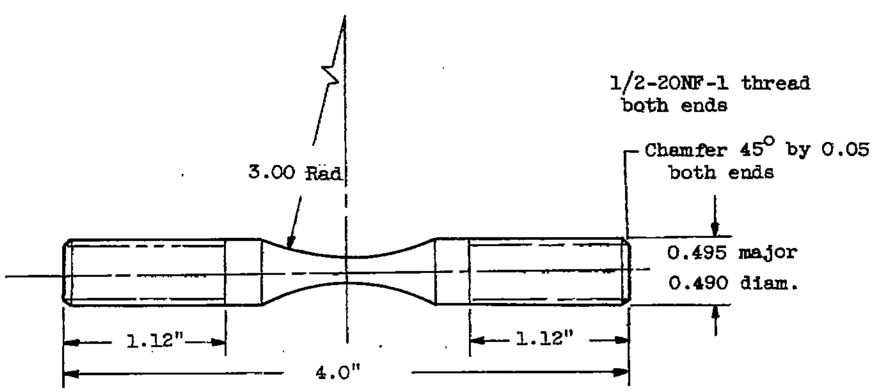


(a) Diamond cross-sectional specimen.



(b) Round cross-sectional specimen

Figure 2. - Fatigue specimens used.

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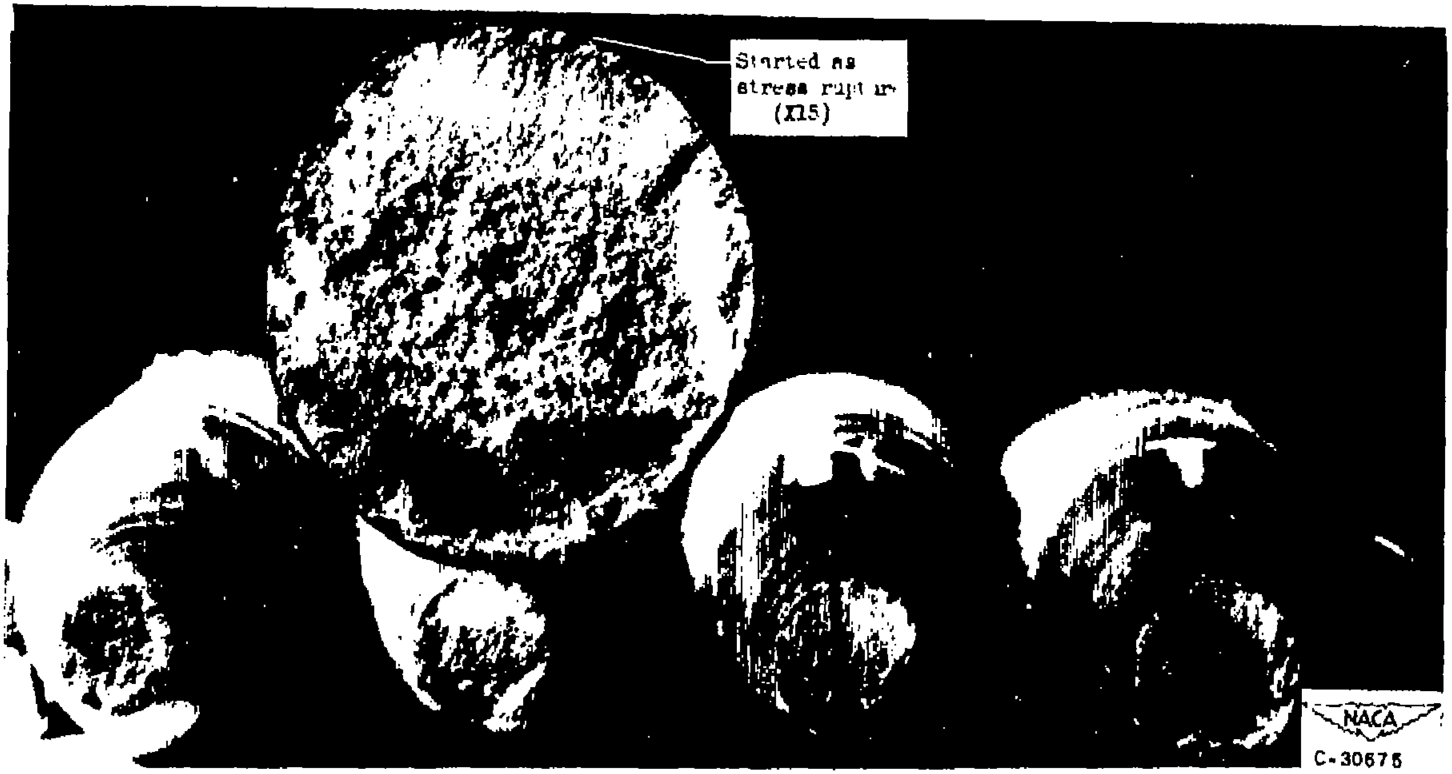
A Drive pulley
B Adjustable cam
C Connecting rod
D Contact
E Loading lever
F Calibrated dial bar
G Contact
H System of fulcrums
I Universal joint
J Specimen adapter
K Furnace
L Specimen adapter
M Universal joint
N Nut
O Piston
P Nut

Figure 3. - Fatigue machine modified for testing at elevated temperatures.

(a) Stress rupture. (b) Stress rupture followed by fatigue. (c) Fatigue.

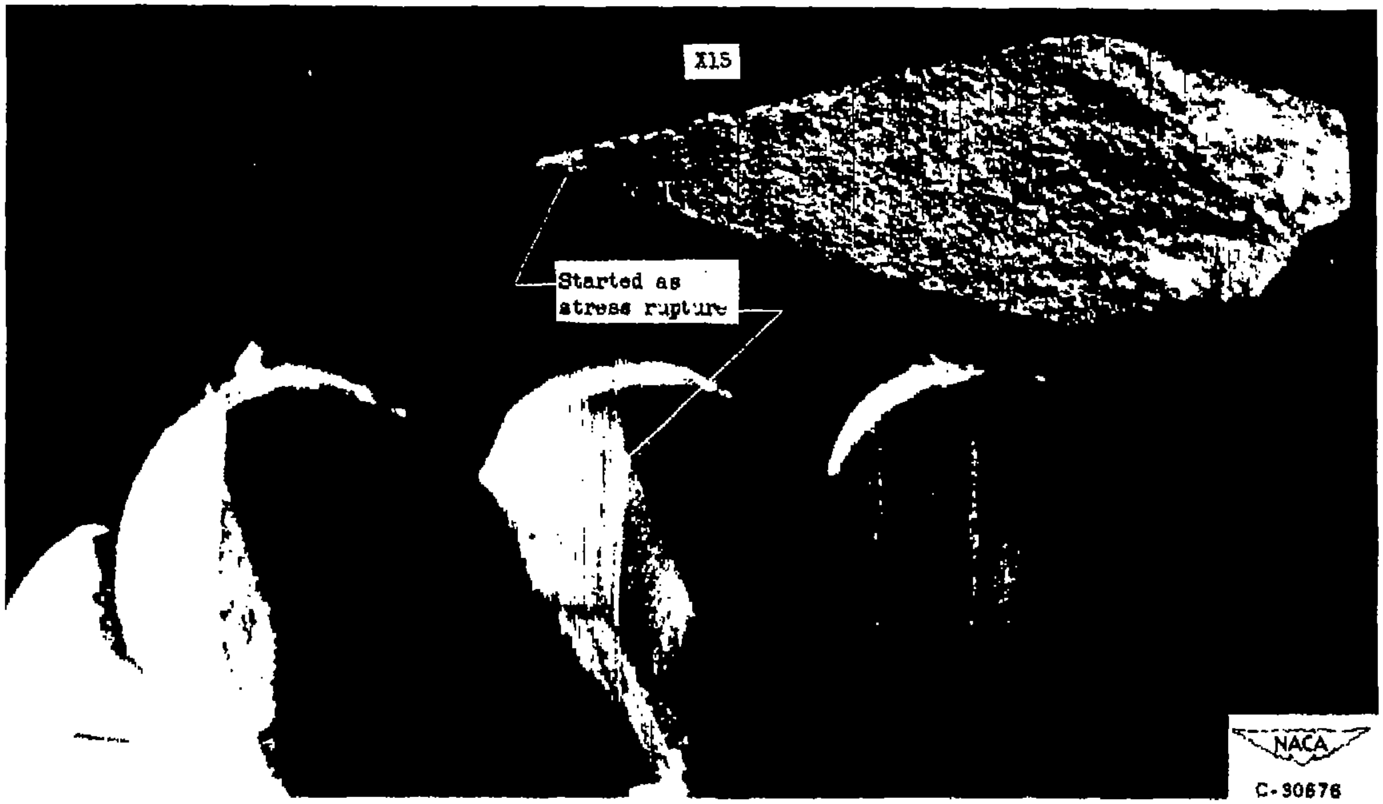
Figure 4. - Types of specimen fracture obtained from tensile-fatigue evaluation of Stellite 21.



Vibratory load, psi	±0	±5000	±10,000	±15,000
Fracture type	Stress rupture	Stress rupture followed by fatigue	Fatigue	Fatigue

(a) Wrought S-816, round cross-sectional specimen.

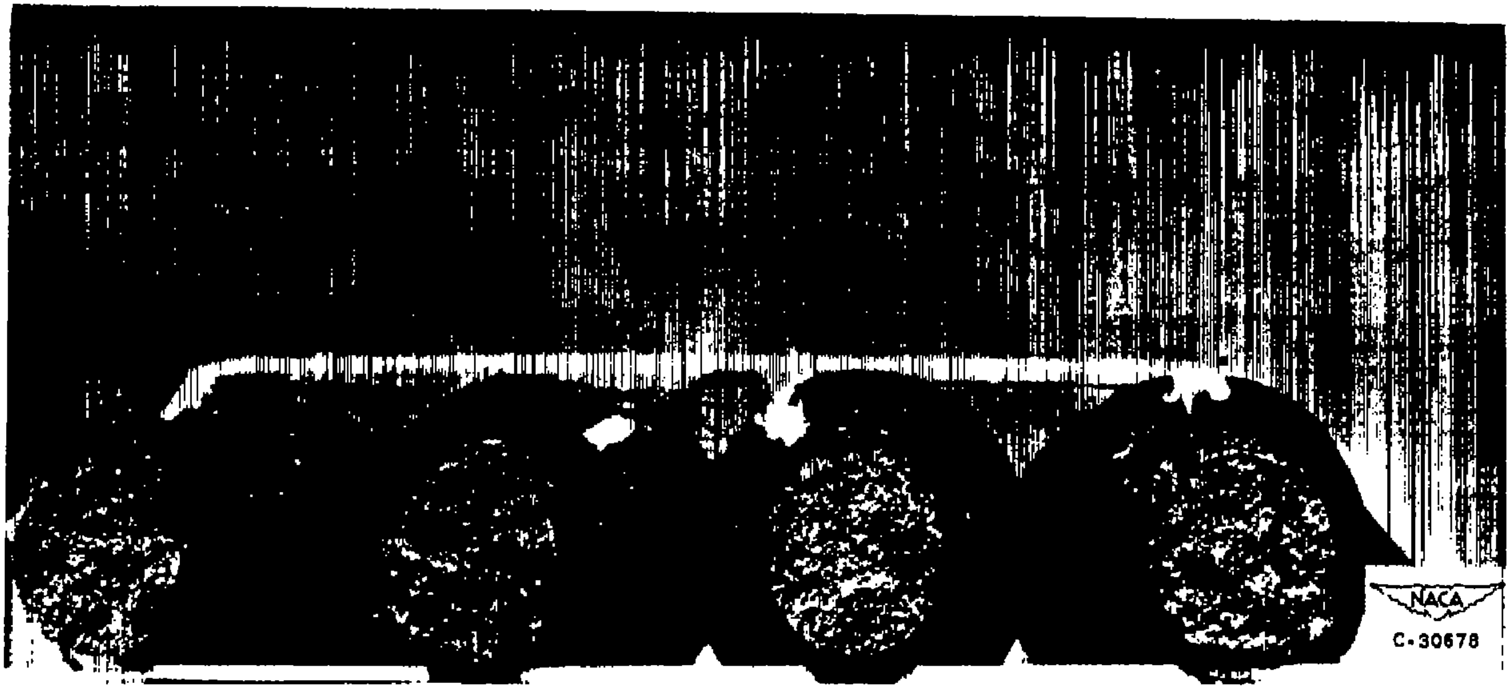
Figure 5. - Effect of magnitude of vibratory load on fractures observed in tensile fatigue evaluation. Mean load, 22,000 pounds per square inch; X4.25.



Vibratory load, psi	±0	±5000	±10,000
Fracture type	Stress rupture	Stress rupture followed by fatigue	Fatigue

(b) Wrought S-816, diamond cross-sectional specimen.

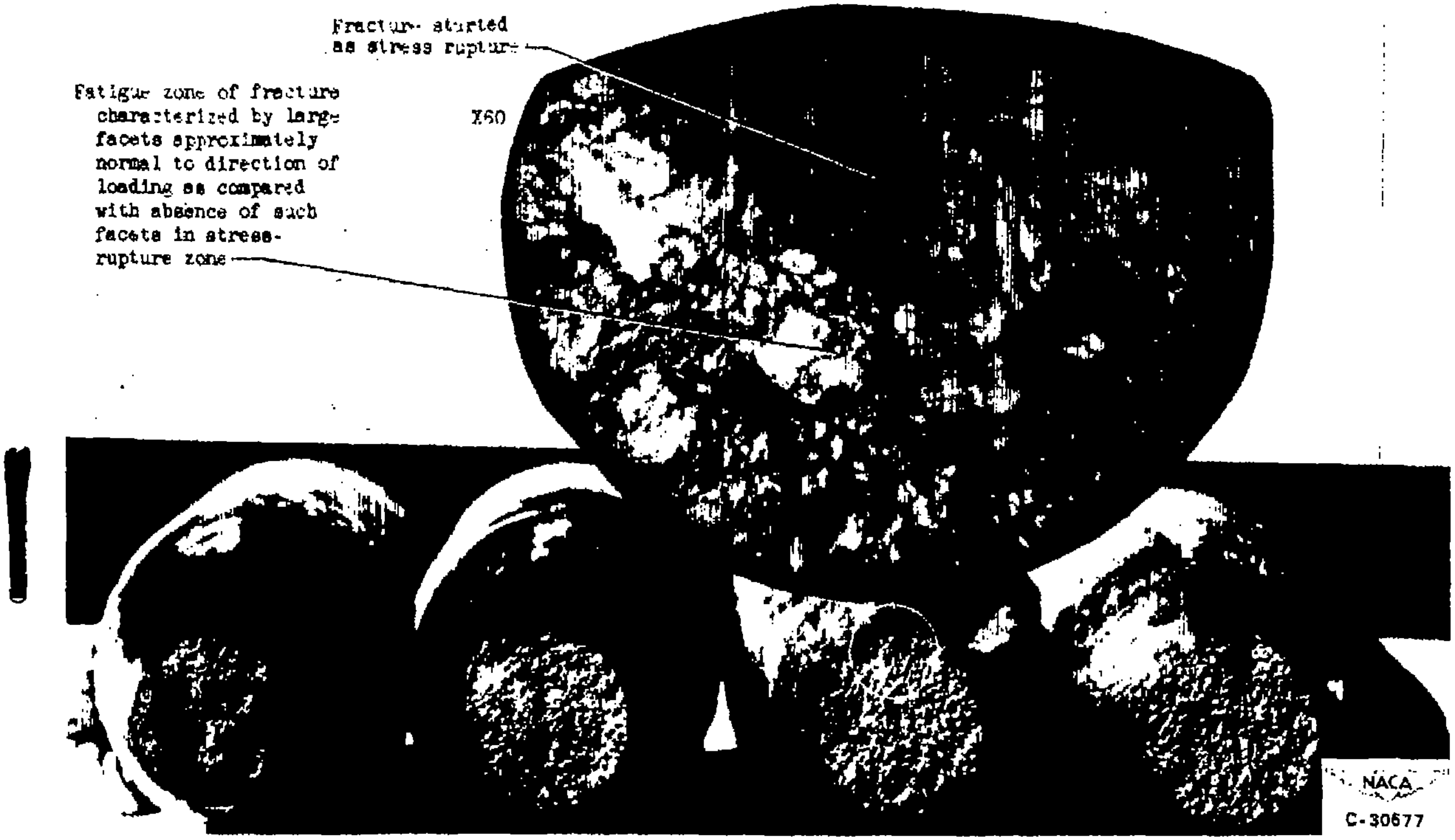
Figure 5. - Continued. Effect of magnitude of vibratory load on fractures observed in tensile fatigue evaluation. Mean load, 22,000 pounds per square inch; X4.25.



Vibratory load, psi	±0	±5000	±10,000	±15,000
Fracture type	Stress rupture	Stress rupture	Stress rupture	Stress rupture

(c) Inconel X.

Figure 5. - Continued. Effect of magnitude of vibratory load on fractures observed in tensile fatigue evaluation. Mean load, 22,000 pounds per square inch; X4.25.



Vibratory load, psi	±0	±5000	±10,000	±15,000
Fracture type	Stress rupture	Stress rupture followed by fatigue	Stress rupture followed by fatigue	Fatigue

(d) Refractalloy 26.

Figure 5. - Concluded. Effect of magnitude of vibratory load on fractures observed in tensile fatigue evaluation. Mean load, 22,000 pounds per square inch; X4.25.

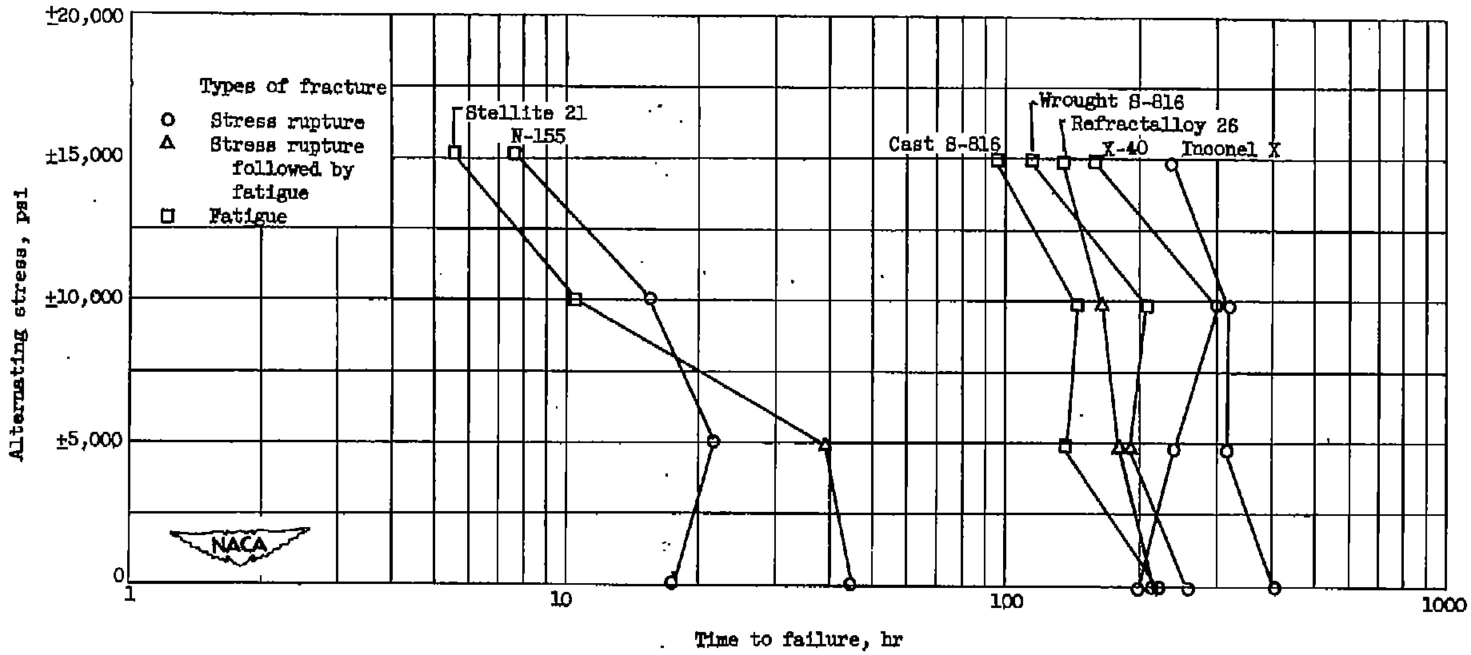


Figure 6. - Effect of alternating stress on type of fracture and time to failure. Temperature, 1500° F; mean stress, 22,000 pounds per square inch.

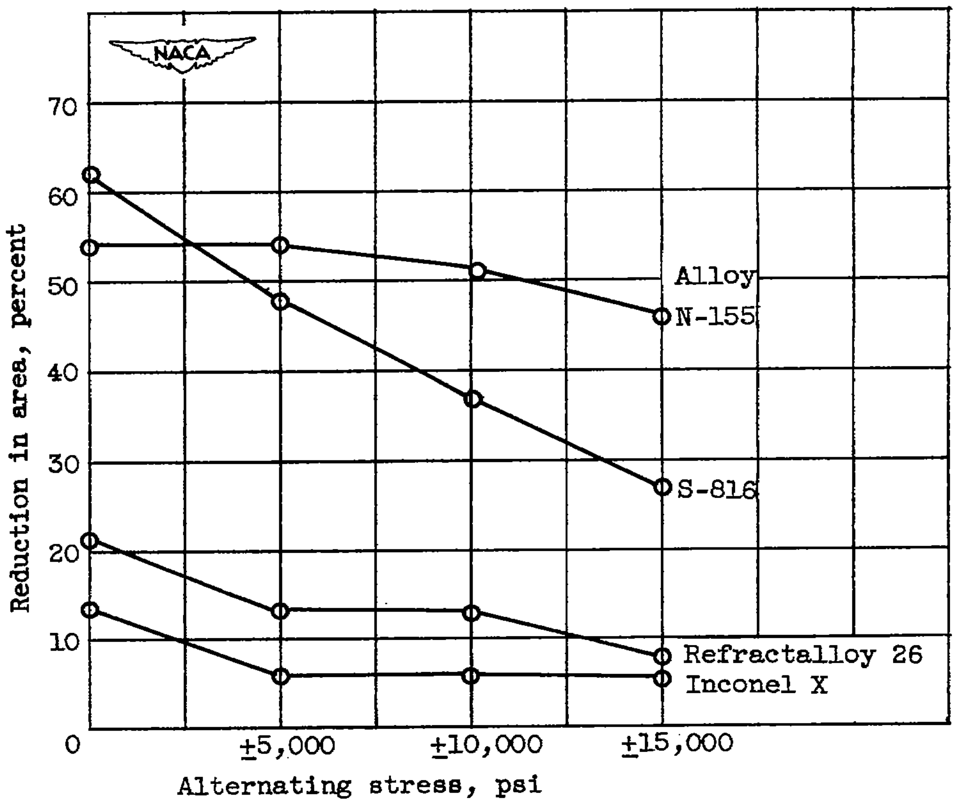


Figure 7. - Effect of alternating stress on reduction of area of fractured specimens.

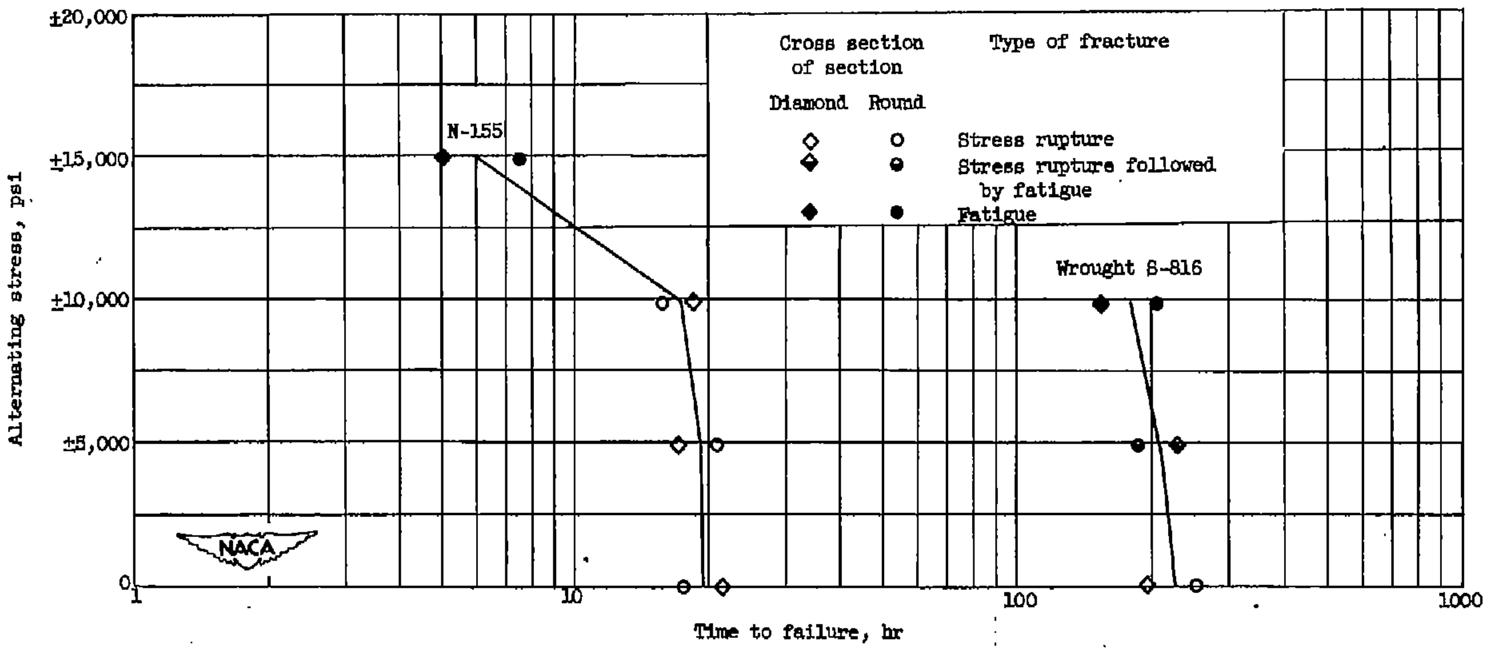
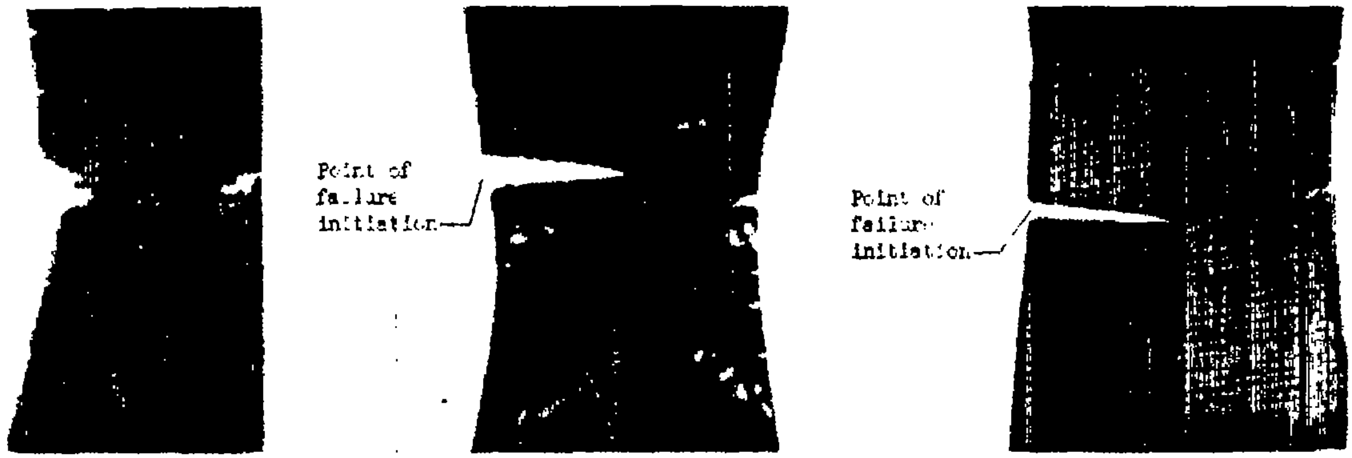


Figure 8. - Effect of specimen shape on time to failure. Temperature, 1500° F; mean stress, 22,000 pounds per square inch.



Alternating stress, psi 0 ±5000 ±10,000

(a) Diamond cross-sectional specimens; X3.75

Alternating stress, psi 0 ±5000 ±10,000 ±15,000

(b) Round cross-sectional specimens; X3.87

Figure 9. - Effect of alternating stress on surface cracking of round and diamond cross-sectional specimens of wrought S-816.

SECURITY INFORMATION

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